RESPONSE LETTER

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Title: Managed Aquifer Recharge in Confined Multi-Layer Aquifers: A Scalable Framework for Drought Resilience in Central Europe

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Response to the Reviewer #2:

General:

The authors present a conceptual, comprehensive and quantitative approach for the identification of aquifer sections most suitable for MAR – measures to combat groundwater resources shortages. The approach presented not only considers the actual suitability of aquifers based on the hydraulic characteristics but also the dynamics of boundary conditions, such as the temporal variability of predicted drought patterns and the availability of infiltration water from surface water bodies by considering hydroecological criteria. The authors build their research on a wealth of data on a number of subcatchments in the Lower Spree area, close to Berlin. This allows the consideration of the large variability of the complex structure of a terrain, formed by glacial action. This approach allows, in my opinion, a generalization of the approach because of the number of catchments considered in the study. Furthermore, the authors present cost estimates as decision making criterion for water resources managers.

In sum: the approach is new, quantitative and also considers the temporal dynamics of water resources as well as that of the availability of recharge water and I recommend publication of the manuscript with minor revision, providing the comments below are being taken care of.

Reviewer's comments:

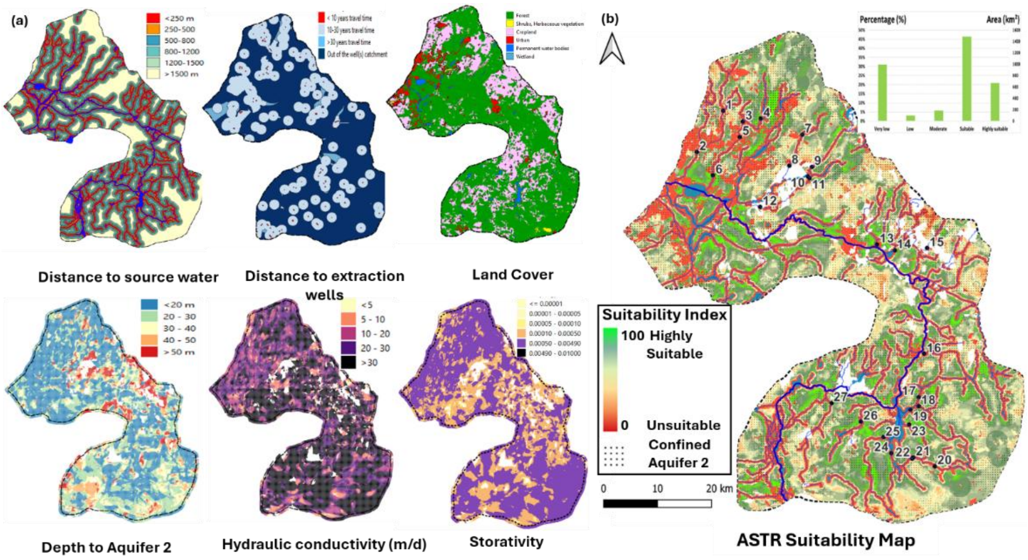
There is one main aspect that requires some more attention by the authors: they claim that their technique applies to confined aquifer systems such as Aquifer 2. In Chapter 3.4 they present the different criteria applied for the ASTR suitability assessment (L239 onwards). One criteria is storativity, a critical property within the context of MAR, especially if the aquifer system is confined, implying feasibility or efficiency of MAR measures. I do recommend that the areas with the aquifer 2 being confined to be outlined in Figure 6f and figure 10.

Authors' response:

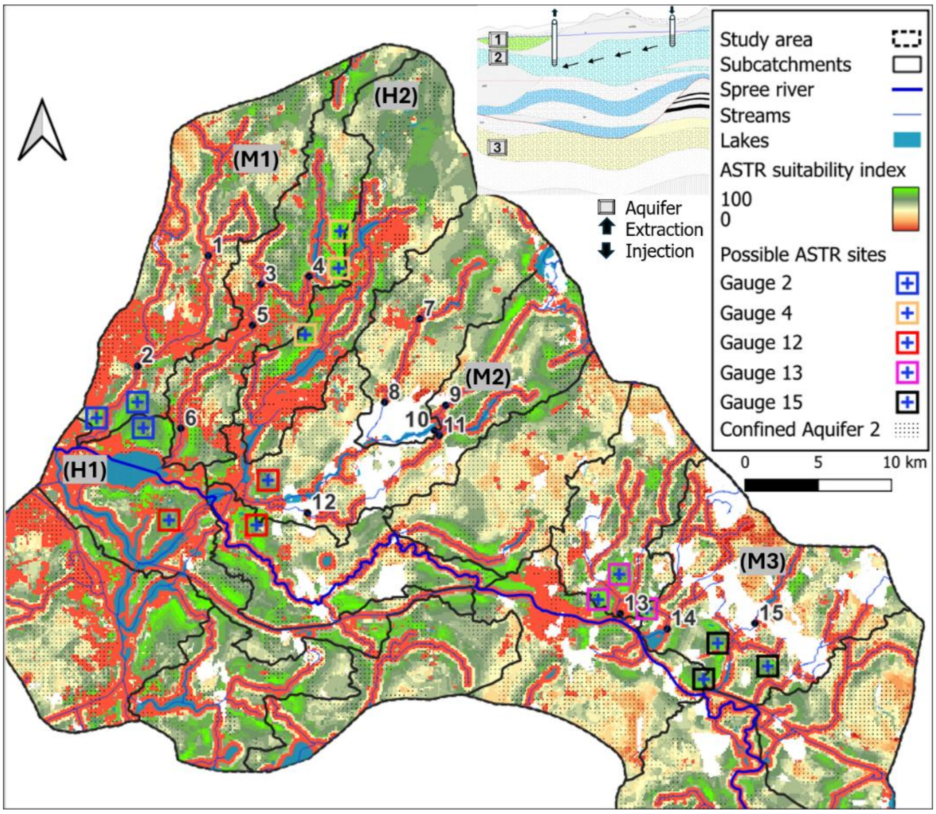
We thank the reviewer for this valuable suggestion. We have updated Figure 6 and Figure 10 to explicitly outline the areas where Aquifer 2 is confined (indicated by the dotted pattern in the legend). Furthermore, we have added a schematic diagram in the top-right corner of Figure 10 to illustrate the ASTR process, demonstrating direct injection into and recovery from the confined Aquifer 2. These visual additions clarify the feasibility of substantial storage volumes and the rationale behind our suitability criteria.

Changes made in the manuscript:

Updated Figure 6



Updated Figure 10



Should artificial recharge be accomplished via the unconfined Aquifer 1 and aquifer 2 be recharged via hydraulic windows, then, different criteria need to be selected on top. In order to clarify the concept for the reader, I recommend to the authors that they present a schematic diagram for different ASTR settings to demonstrate the feasibility of substantial volumes of storage, as well as the expansion of the suitability criteria. (schematic diagram in the Updated Figure 10)

Authors' response:

We thank the reviewer for raising this important conceptual point. As clarified in the updated schematic diagram (Figure 10), our framework specifically evaluates direct injection and recovery within the confined Aquifer 2. Because the study focuses on this direct pathway, the current suitability criteria (e.g., Aquifer 2 storativity and hydraulic conductivity) are fully appropriate. We have added a clarifying sentence in Section 3.4 to explicitly distinguish the evaluated direct ASTR setting from the indirect pathway via Aquifer 1, explaining why the criteria were not expanded to cover the latter.

Changes made in the manuscript:

Section 3.4 (After line 265)

To clarify the conceptual framework for the reader, the schematic diagram in Figure 10 illustrates that this study specifically evaluates direct injection and recovery within the confined Aquifer 2. While indirect recharge via the unconfined Aquifer 1 and subsequent leakage through hydraulic windows represents an alternative ASTR setting, it requires distinct hydrogeological criteria and is therefore excluded from the current suitability assessment.

In order to make the results better "digestible" and in order to provide maximum use of the study for the reader, I recommend the authors to provide a table, listing all 24 catchments with individual columns specifying catchment characteristics (material properties, groundwater regime (confined/unconfined), ASTR suitability and in the final column the reason why it was selected suitable /unsuitable). This analysis should then be picked up, grouped into catchment classes and conclusions discussed after L 508.

Authors' response:

We thank the reviewer for this constructive suggestion. We have added a new table (Table S2 in the Supplementary Material) that lists all assessed catchments. The table includes individual columns specifying material properties (Mean Hydraulic Conductivity and Mean Storativity), the percentage distribution of the groundwater regime (confined, unconfined, and no aquifer), the mean MCDA suitability score, the final ASTR suitability classification, and a brief rationale for each classification. Furthermore, we have added a paragraph after Line 508 grouping the sub-catchments into three classes (Highly Suitable, Suitable, and Moderately/Low Suitable) based on their hydrogeological properties and MCDA scores, as detailed in the new Table S2. This classification provides a clear, prioritized roadmap for water resources managers to focus pilot projects on the most viable catchments.

Table S2: Catchment characteristics and ASTR suitability assessment.

Sub catchment	Aquifer Properties (Mean K m/d &Mean S)	Groundwater Regime % (Confined & Unconfined & No Aquifer)	MeanS1 Suitability (%)	ASTR Suitability	Reason
1	18.7 & 6.6e-4	67.6 & 30.0 & 2.4	56	Moderately Suitable	Moderate permeability; confined dominates
2	16.8 & 5.0e-4	57.3 & 31.2 & 11.5	69	Suitable	Good S1, but notable no-aquifer area
3	16.5 & 1.2e-3	56.3 & 43.2 & 0.5	69	Suitable	Highest storativity; aquifer almost fully present
4	16.7 & 6.1e-4	34.9 & 50.4 & 14.8	61	Moderately Suitable	Unconfined dominates but significant no-aquifer areas
5	19.3 & 1.3e-3	34.8 & 52.5 & 12.7	60	Moderately Suitable	High Kz & storativity, but reduced by no-aquifer areas
6	16.6 & 9.6e-4	71.9 & 28.1 & 0.0	69	Suitable	Aquifer fully present; good S1 despite confinement
7	15.3 & 7.5e-4	63.0 & 36.0 & 1.0	62	Suitable	Lower Kz but acceptable, aquifer mostly present
8	17.3 & 6.7e-4	77.5 & 20.9 & 1.7	74	Highly Suitable	Highest S1; excellent properties despite confinement
9	21.0 & 3.8e-4	74.0 & 20.2 & 5.8	71	Highly Suitable	Highest permeability; excellent for injection
10	19.9 & 6.5e-4	68.1 & 31.7 & 0.2	67	Suitable	High Kz, aquifer almost fully present
11	19.2 & 4.9e-4	42.3 & 48.0 & 9.8	56	Moderately Suitable	Balanced regime but low storativity & significant NA
12	18.8 & 5.2e-4	69.5 & 18.7 & 11.8	60	Moderately Suitable	Confined + large no-aquifer area limit potential
13	18.9 & 1.2e-3	47.2 & 52.7 & 0.1	64	Suitable	Excellent storativity, unconfined dominates
14	19.2 & 6.1e-4	50.3 & 43.5 & 6.3	62	Suitable	Balanced regime, good overall properties
15	17.6 & 4.1e-4	46.5 & 25.6 & 27.9	54	Low Suitability	Largest no-aquifer area, lowest S1. Not recommended
16	19.0 & 8.8e-4	36.2 & 60.5 & 3.3	62	Suitable	Unconfined dominates, good storativity
17	20.3 & 6.2e-4	49.8 & 44.6 & 5.6	63	Suitable	High Kz, balanced regime
18	19.6 & 8.5e-4	36.5 & 62.4 & 1.0	64	Suitable	Unconfined dominates, aquifer almost fully present
19	16.1 & 6.8e-4	52.7 & 46.3 & 1.1	65	Suitable	Moderate Kz but good S1; aquifer mostly present
20	20.8 & 6.9e-4	49.1 & 38.6 & 12.3	68	Suitable	High Kz, good S1, but notable no-aquifer area
21	18.1 & 8.1e-4	60.4 & 36.6 & 3.0	58	Moderately Suitable	Confined dominates, moderate S1

Changes made in the manuscript:

Discussion (after L 508)

To enhance the practical application of these results, we classified the assessed sub-catchments based on their hydrogeological characteristics and ASTR suitability (Table S2). Highly Suitable includes sub-catchments 8 and 9, which show excellent hydraulic properties and minimal "no aquifer" areas, making them priority candidates for ASTR implementation. Suitable comprises most sub-catchments (e.g., 2, 3, 6, 7, 10, 13, 14, 16-20) with good overall conditions and MCDA scores of 60–70%, while Moderate to Low Suitability includes areas limited by lower storativity or extensive "no aquifer" zones. This classification supports prioritization of pilot projects in highly and suitable catchments to maximize drought resilience benefits.

L227: RCP8.5 is highly unlikely; needs a statement, why it is considered here.

Authors' response:

We thank the reviewer for raising this important point. We acknowledge that the reference to RCP8.5 was incorrect. In this study, we do not use RCP-based results; instead, we consider socio-economic development pathways based on the SSP framework (specifically SSP1-2.6 and SSP2-4.5), consistent with IPCC AR6. We have entirely removed RCP8.5 from all calculations, figures, and text in the manuscript. To address the specific points raised:

(i) Climate projections are based on regionalized datasets (UBA) derived from established CMIP ensembles.

(ii) Socio-economic assumptions are represented through SSP pathways and integrated using sector-specific water demand projections from local stakeholders (BWB, Adelphi Research, ZALF).

(iii) Yes, the projected climate variables were bias-corrected and calibrated against historical observations within the hydrological model to ensure reliable simulations.

Changes made in the manuscript:

Section 3.3 (Lines 227-228)

Projections were developed using SSP pathways (SSP1-2.6 and SSP2-4.5), consistent with IPCC AR6 and UBA regional climate projections (Kreienkamp et al., 2022). These pathways represent different socio-economic trajectories and were linked to sector-specific water demand projections from local stakeholders (BWB, Adelphi Research, ZALF). Climate variables were bias-corrected and calibrated against historical meteorological and hydrological records within the SWIM model to ensure reliable water-balance estimates.

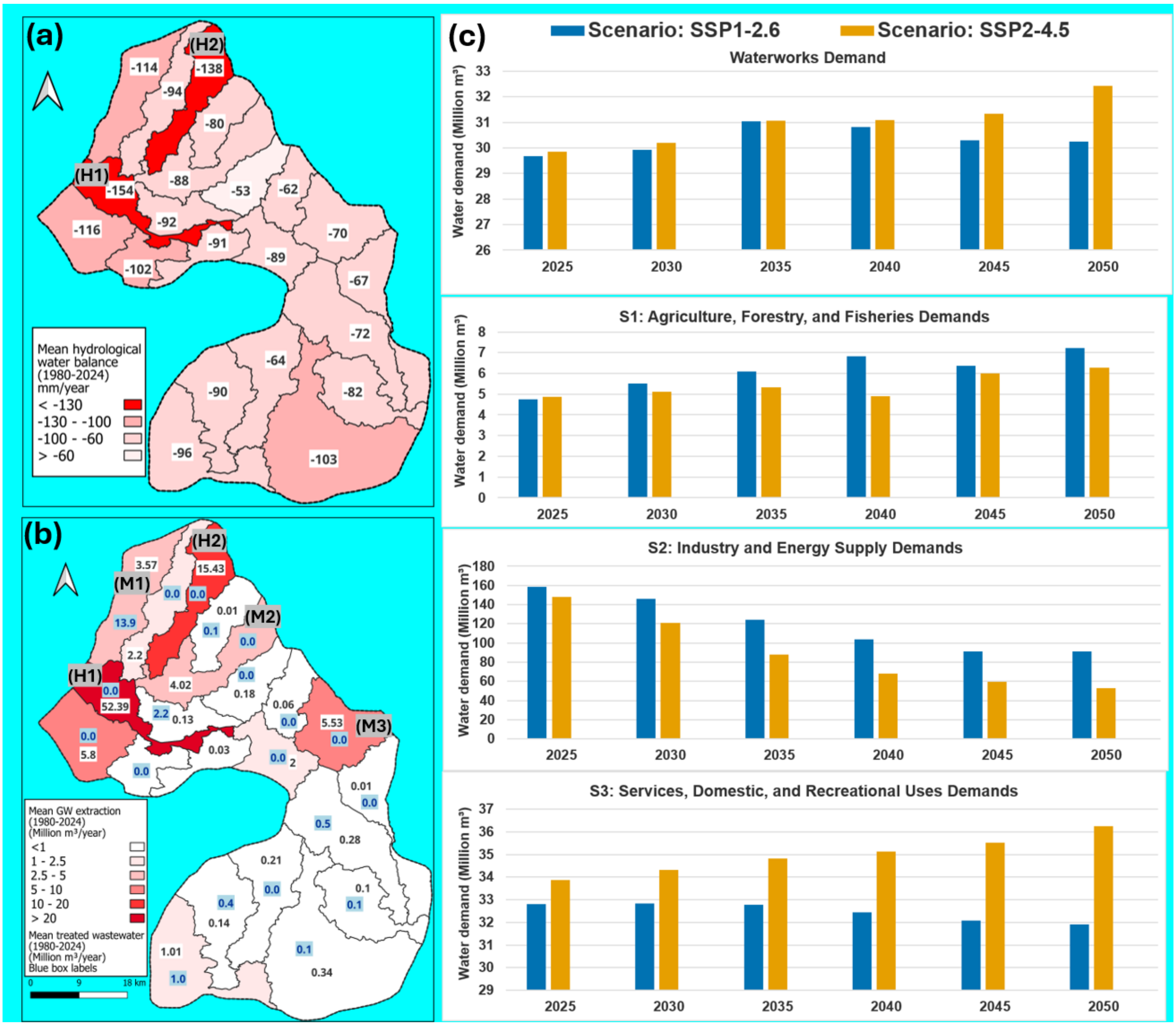
Section 4.2 (Lines 360-373)

We analysed projected water-demand scenarios for 2025-2050 and found a moderate but steady increase in total waterworks demand across the considered scenarios (Fig. 5c). Under SSP1-2.6, total waterworks demand fluctuates around 30-31 Mm^3, while the most-likely SSP2-4.5 scenario shows a modest increase from ~30 to ~32 Mm^3 by 2050. This spread (~1-2 Mm^3) defines the stress-test range for storage and recovery capacity under realistic future conditions.

Sectoral patterns exhibit contrasting dynamics. S1 (Agriculture, Forestry, and Fisheries) shows a consistent upward trend, reflecting higher irrigation needs under warmer conditions. S2 (Industry and Energy) declines markedly due to improvements in water-use efficiency and structural transitions. The decline is most pronounced under SSP2-4.5 (from ~150 to ~55 Mm^3). Despite the decrease, S2 remains the dominant contributor to total variance and peak loads. S3 (Services, Domestic, and Recreational Uses) diverges across scenarios: slightly decreasing under SSP1-2.6 (~33 to 31 Mm^3) and gradually increasing under SSP2-4.5 (~34 to 37 Mm^3), with pronounced seasonal peaks during summer months.

Changes made in the manuscript:

Updated figure 5c



L243: Hydraulic conductivity – Kvertical?

Authors' response:

We thank the reviewer for this precise question. We have clarified in Section 3.4 (Line 243) that the hydraulic conductivity values used in our regional screening refer to the horizontal hydraulic conductivity (HK), as it governs the lateral spread of the injected water and recovery well yields at the regional scale. We also added a clear statement acknowledging that while vertical hydraulic conductivity is critical for local injection efficiency, its detailed evaluation is beyond the scope of this regional screening and is reserved for future site-specific pilot designs.

Changes made in the manuscript:

Section 3.4 (Line 243)

Horizontal hydraulic conductivity (HK): We prioritized areas with higher HK values, as they facilitate the lateral spread of the injected water plume and support sustainable recovery well yields at the regional scale. Suitability scores ranged from 5 (>30 m/d) to 1 (<5 m/d). We acknowledge that vertical hydraulic conductivity is also critical for local injection efficiency; however, its detailed evaluation is beyond the scope of this regional screening and is reserved for future site-specific pilot designs.

- Is there any weighting considered between the different criteria

Authors' response:

We thank the reviewer for raising this critical point regarding MCDA weighting. We have now explicitly detailed a sensitivity analysis in Section 3.4 (and added Table S3 in the Supplementary Material) comparing three weighting scenarios: equal weighting (S1), hydrogeology-heavy (S2), and distance-heavy (S3). We retained S1 as our primary model because it provides a robust, unbiased baseline that ensures the framework's transferability. However, the analysis demonstrates that local decision-makers can easily adapt the framework using S2 or S3 based on specific regional priorities.

Changes made in the manuscript:

Section 3.4 (Lines 262-265)

We combined all criteria using a weighted overlay approach. To address potential subjectivity in criterion weighting, we conducted a sensitivity analysis comparing three scenarios: S1 (equal weighting), S2 (hydrogeology-focused, prioritizing storativity and conductivity), and S3 (distance-focused, prioritizing proximity to source water and wells). This analysis demonstrates the framework's robustness and transferability without relying on single-factor prioritization (Table S3 in the Supplementary Material).

Section 4.3 (After L 395)

To validate that the suitability map is not driven by arbitrary weighting, we evaluated the three scenarios (Table S3). The results demonstrate high robustness: the "Very Low" suitability class remained remarkably stable at ~29% across all scenarios (variation <0.3%), indicating that physical constraints consistently define unsuitable areas. While the "Suitable" and "Highly Suitable" classes showed moderate percentage variations (e.g., Highly Suitable ranged from 17.2% in S3 to 27.7% in S2), the spatial distribution of these high-priority zones remained geographically consistent across all scenarios (Fig. 6). This confirms that site suitability is primarily controlled by underlying physical characteristics rather than subjective weight assignments.

Supplementary Material (Table S3)

Table S3: MCDA weighting scenarios for sensitivity analysis

Scenarios	Storativity	Hydraulic conductivity	Depth	Land Use	Distance to source	Distance to wells
S1 (equal weight)	0.167	0.167	0.167	0.167	0.167	0.167
S2 (hydro-heavy)	0.25	0.25	0.20	0.10	0.10	0.10
S3 (distance-heavy)	0.10	0.10	0.10	0.15	0.275	0.275

Section 4.3 (revised text)

We developed an ASTR suitability map using GIS-MCDA (Fig. 6). The analysis integrated six criteria (Fig. 4a), classified into five classes: very low (0-20), low (21-40), moderate (41-60), suitable (61-80), and highly suitable (81-100).

Sensitivity Analysis Results: We tested three weighting scenarios (Table 2). Results demonstrate high robustness (Fig. 6; Table 3). The "Very Low" suitability class remained stable at ~29% across all scenarios (variation <0.3%), indicating physical constraints consistently define unsuitable areas. The "Suitable" class showed moderate variation (36.7-43.3%; Δ = 6.6%), while "Highly Suitable" areas varied between 17.2% (S3) and 27.7% (S2) (Δ = 10.5%).

Despite percentage variations, the spatial distribution of high-suitability zones remained geographically consistent across all scenarios (Fig. 6a-c), confirming that site suitability is primarily controlled by underlying physical characteristics rather than subjective weight assignment (Hani et al., 2023; Vandala and Mahed, 2025).

Baseline Scenario (S1) Results: Under the equal-weight baseline scenario (S1), 19.5% of the area (670 km²) was highly suitable, and 43.3% (1,484 km²) suitable. Combined, 62.8% of the catchment (2,154 km²) is viable for ASTR. Highly suitable zones concentrate where Aquifer 2 has higher storativity ($>5\times10^{-3}$) and K (>30 m/d), optimal distances to rivers (500–800 m) and wells (<10 years travel time), and minimal land-use conflicts.

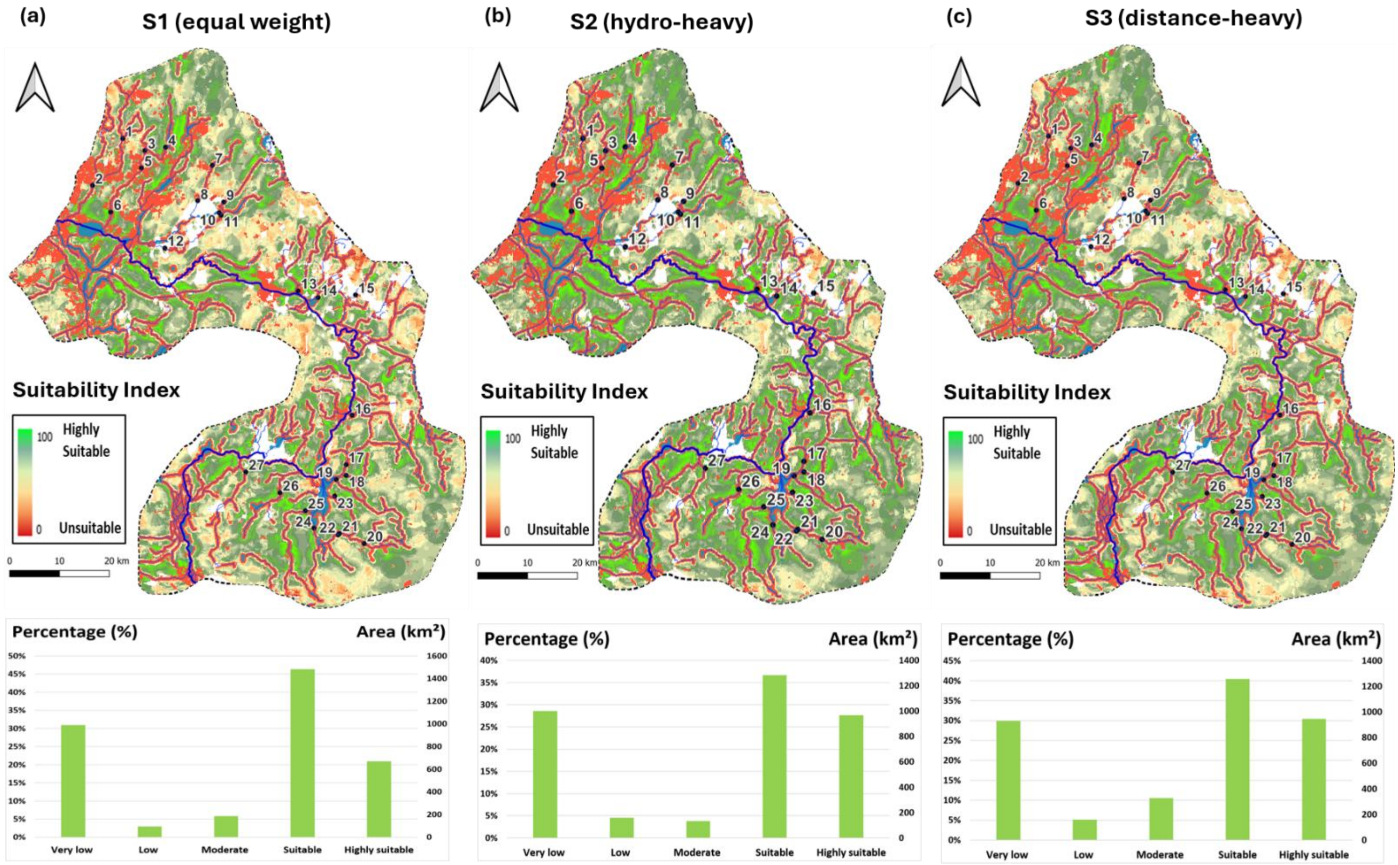


Figure 6. Sensitivity analysis of ASTR site suitability under three MCDA weighting scenarios: (a) S1 (equal weight), (b) S2 (hydro-heavy), and (c) S3 (distance-heavy). Bar charts show the percentage (%) and area (km²) per suitability class. The consistent spatial distribution of high-suitability zones across scenarios demonstrates the robustness of the MCDA results to criterion weighting. See Tables 2–3 for detailed weights and distributions.

Table 3: Suitability class distribution across weighting scenarios

Suitability class	S1 (%)	S2 (%)	S3 (%)	S1- S2	S1- S3
Very low	28.92	28.63	28.84	0.29	0.08
Low	2.82	3.21	2.92	-0.39	-0.1
Moderate	5.4	3.78	10.56	1.62	-5.16
Suitable	43.31	36.72	40.46	6.59	2.85
Highly suitable	19.56	27.66	17.22	-8.1	2.34

L239 or L268: A statement is required comparing the method presented here with others already published..

Authors' response:

We thank the reviewer for this important point. We have added a statement at the end of Section 3.4 comparing our method to existing published frameworks. We highlighted that while conventional MCDA studies rely primarily on static hydrogeological criteria, our framework uniquely integrates dynamic hydroclimatic (SPEI/SGI) and ecological flow thresholds, providing a more robust spatiotemporal assessment for drought resilience.

Changes made in the manuscript:

Section 3.4 (After L265)

Unlike conventional MAR suitability studies that primarily rely on static hydrogeological and spatial criteria (e.g., Khalil et al., 2022), the framework presented here integrates dynamic hydroclimatic and ecological constraints. By coupling the static GIS-MCDA with time-series drought indices (SPEI/SGI) and ecological flow thresholds, our approach transitions from a purely spatial assessment to a spatiotemporal evaluation. This ensures that identified suitable sites are not only hydrogeologically viable but also climatically resilient and ecologically sustainable, addressing a critical gap in existing MAR planning methodologies.

L347: What time intervals are used for the computation? Year/month/day?

Authors' response:
We thank the reviewer for pointing out the need for clarity regarding temporal resolutions. We have added a summary in Section 3.1 explicitly stating the time intervals used: daily data for SPEI and flow-threshold analysis, monthly records for SGI, and monthly-to-annual aggregation for the water balance.

Changes made in the manuscript:

Section 3.1 (Line 189)

To ensure reproducibility, computations used the following temporal resolutions: daily data for SPEI (aggregated to 12-month periods) and flow-threshold analysis; monthly records for SGI; and monthly-to-annual aggregation for the water balance.

L231: Schematic Diagram of ASTR – Process needs to be included

Authors' response:

We have added a direct reference to the ASTR process schematic diagram (now included in Figure 10). This ensures the reader is immediately guided to the visual explanation of the direct injection and recovery process in the confined Aquifer 2.

Changes made in the manuscript:

Figure 10 caption (Line 460)

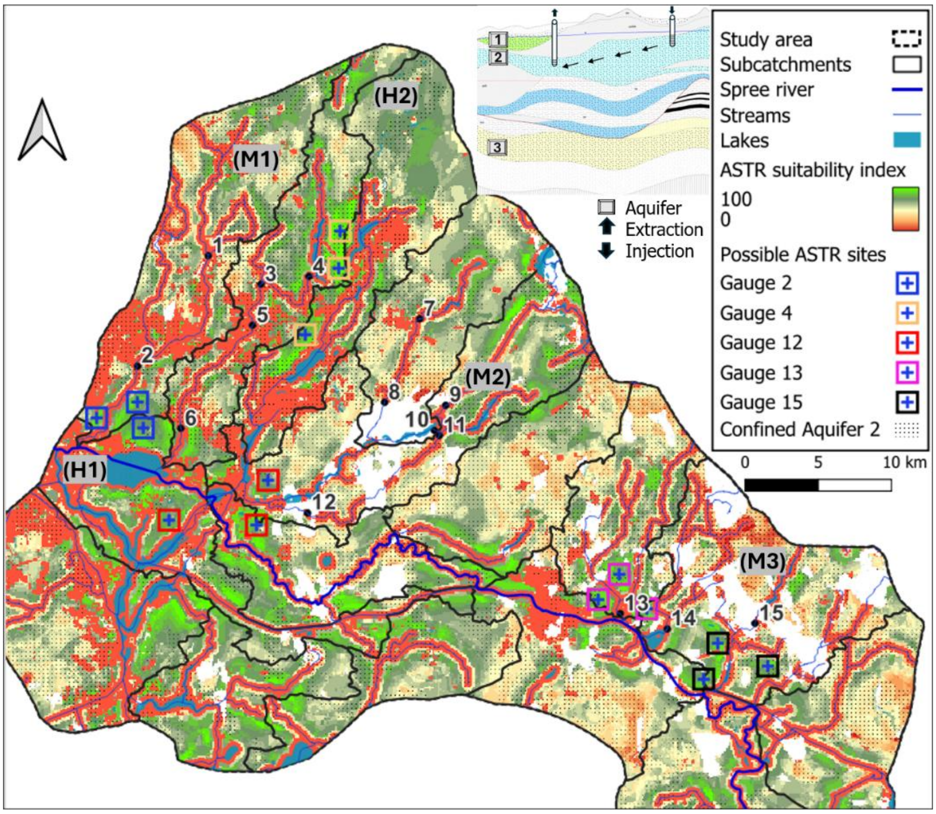


Figure 10. Streamflow-driven ASTR suitability across the catchment, with candidate recharge sites at Gauge 2 (blue), Gauge 4 (orange), Gauge 12 (red), Gauge 13 (pink), and Gauge 15 (dark blue); stressed sub-catchments (H1, H2, M1–M3) are labelled, highlighting where monitored surplus streamflow aligns with favorable hydrogeology for ASTR. The inset schematic diagram illustrates the conceptual ASTR process involving direct injection and recovery in the confined Aquifer 2.